REMARKS

Applicant has amended the claims 1, 3, 6, 7, 10, 14, 16 through 19, 21 through 23, 25 and 27 through 30 and also canceled the claims 12, 13 and 26 without prejudice. Applicant respectfully submits that these amendments to the claims are supported by the application as originally filed and do not contain any new matter. Accordingly, the Office Action will be discussed in terms of the claims as amended.

The Examiner has objected to the claims 1, 4 through 6, 7, 10 through 28, 29 and 30. Applicant has amended the claims and respectfully submits that the claims 1, 4 through 6, 7, 10, 11, 14 through 25 and 27 through 30 are not now objectionable.

The Examiner has rejected the claims 17 through 28 under 35 USC 112, first paragraph stating that they fail to comply with the embodiment requirement. In reply thereto, Applicant has amended the claims 17 through 19, 21 through 23, 25, 27 and 28 and canceled the claim 26 without prejudice. Accordingly, Applicant respectfully submits that the claims 17 through 25, 27 and 28 all comply with the requirements of 35 USC 112, first paragraph.

The Examiner has rejected the claims 1 through 6, 7 through 16, 17 through 21 and 22 through 28 under 35 USC 103 as being obvious over Orlov et al. in view of Heanue et al. stating that Orlov et al. teaches a holographic storage and retrieval system that is comprised of a first spatial modulator for spatially modulating a light from a source 16 generated an information light or signal light and a reference generator for spatially modulating a light from a source 16 and generating a reference light with the signal for information light and reference light directed to an object lens with the area of the reference light at the entrance of the lens, surrounds the area of the signal or information light and it is implicitly true that the spatial light modulator for modulating the information or signal light implicitly has a plurality of pixels, but does not disclose that the reference generator, disposed at the periphery of the first spatial light modulator, comprises also a spatial light modulator and instead teaches that the reference generator may include a diffuser, lenses, face plate or optical system; Heanue et al. teaches that a diffuser or face plate may be provided by a spatial light modulator; and it would have been obvious to one of ordinary skill in the art to replace the diffuser in Orlov et al. with the spatial light modulator of Heanue et al.

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In reply to this rejection, Applicant has carefully reviewed both Orlov et al. and Heanue et al. and respectfully submits that neither discloses that the reference light is in a radial pattern, the traveling direction of the reference light is directed in a direction other than an optical axis and the radial pattern of the reference light is asymmetric with respect to a virtual center, all of which are limitations of Applicant's claims.

Still further, the Examiner points out that the description in Orlov et al. reads that the diffuser 28 produces a speckle pattern in reference beam 32 and is thus adapted for shift speckle multiplexing and suggests that this language discloses a radial pattern. In reply thereto, Applicant respectfully submits that the Examiner is technically incorrect. In particular, Applicant respectfully submits that the reference light of Orlov et al. forms only a speckle pattern when the lights scattered by the diffuser interfere. In other words, Orlov et al. discloses interference between the reference lights and Applicant respectfully submits it is therefore opposite from Applicant's invention.

In addition, Applicant respectfully submits that the advantages of Applicant's invention cannot be achieved by the construction of Orlov et al. or Orlov et al. in conjunction with Heanue et al. In particular, and as exemplified by the attached publication entitled: "Analysis of a co-linear holographic storage system: Introduction of pixel spread function", the use of a reference light into a radial pattern causes reproduction of the image that is superior to a concentric pattern or a random pattern, such as is used by the prior art.

In view of the above, therefore, Applicant respectfully submits that the combination suggested by the Examiner is not Applicant's invention and the claims 1 through 11, 14 through 25 and 27 through 30 are not obvious over Orlov et al. in view of Heanue et al.

Applicant further respectively and retroactively requests a two (2) month extension of time to respond to the Office Action and respectfully request that the extension fee in the amount of $245.00 be charged to QUINN EMANUEL DEPOSIT ACCOUNT NO. 50-4367.

In view of the above, therefore, it is respectfully requested that this Amendment be entered, favorably considered and the case passed to issue.

Please charge any additional costs incurred by or in order to implement this Amendment or required by any requests for extensions of time to QUINN EMANUEL DEPOSIT ACCOUNT NO. 50-4367.

Respectfully submitted,

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Date

Analysis of a collinear holographic storage system: introduction of pixel spread function

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Image formation in a collinear holographic storage system was analyzed. The wavefront from each pixel of a spatial light modulator was regarded as a plane wave in the recording medium, and its wave vector was determined by the position of the pixel. The hologram in the recording medium was treated as the summation of all gratings written by all combinations of two plane waves. The image of a data page was formed by diffraction of the reference waves by all gratings. The results of the simulation showed good agreement with experiment. We introduced the pixel spread function to describe the image formation characteristics. Analysis of the pixel spread function reveals that a radial-line pixel pattern for reference waves gave a sharper image than other reference pixel patterns. It is also shown that a random phase modulation applied to each reference pixel improved the image formation. © 2006 Optical Society of America

OCIS codes: 210.2860, 110.2990, 210.4590, 090.7330.

Collinear holographic storage systems have significant advantages,[1-3] such as a low bit error rate, a uniform shift selectivity for both radial and tangential directions, and fairly large wavelength shift and tilt tolerance. However, no detailed theoretical analysis of such systems has been reported so far, and their performance has not yet been satisfactorily explained. In this Letter we present a simple model to explain image formation in a collinear holographic storage system, and we consider the image formation process of signal pixels of a spatial light modulator (SLM) using various reference patterns. We introduce an image evaluation metric called the pixel spread function (PxSF) which has a function similar to the point spread function[4] (PSF) used in linear imaging systems. We explain that the PxSF is determined only by the optical system and is independent of the data image pattern. Thus, by examining the variation of PxSF as a function of the distance from the optical axis of the system, we can qualify the sharpness of the image. Note that in this Letter our purpose in performing the simulation is not to predict the experimental results quantitatively but to gain a physical insight into image formation in the collinear holographic system.

A model of the optical system used to analyze image reconstruction in the collinear holographic storage system is shown in Fig. 1. In practice, a SLM and a recording medium were placed at the two focal planes of an objective lens. In the model, because a real holographic disc has a mirror on the back surface of the recording medium, the thickness of the recording medium was doubled, and a mirror image of the system was placed after the medium. At the image position of the SLM, a two-dimensional detector array was placed. We assumed that each pixel of the SLM was perfectly imaged at a corresponding pixel of the detector array. A page of data was displayed on an inner area of the SLM, and the pixels in the surrounding area provided a reference wave.[1-3]

We treated each pixel of the SLM as a small square aperture that was opened or closed according to the ON or OFF state of the pixel. The pixel arrangement was assumed to be a regular rectangular array, and the pixel pitches were the same for both x and y directions. The SLM was illuminated by a coherent plane wave. Light transmitted through a pixel propagated to the objective lens. As typical dimensions for the system, when we assumed that, for example, the aperture size of the pixel was 15 μm × 15 μm, the focal length of the lens f was 5 mm, and the wavelength was 0.5 μm. With these dimensions, the Fresnel number was 0.09. This means that the diffracted wave just before the lens was in the Fraunhofer regime and had a spherical wavefront and an amplitude represented by a two-dimensional sinc function. After the lens, the wavefront propagating from each pixel was a plane wave.

Here we represent the position of a pixel (i,j) on the SLM as (x_i, y_j), and then the wave vector k_{ij} of the corresponding plane wave is determined uniquely. When the objective lens maintains the sine condition

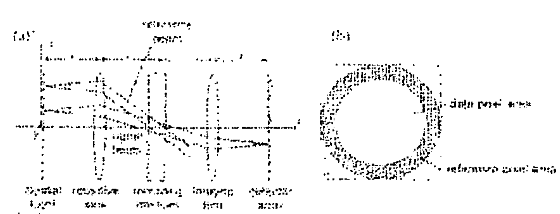

Fig. 1. Model for image-formation analysis in the collinear holographic storage system. (a) Optical system. (b) Arrangement of pixels on the spatial light modulator.

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the wave vector of the plane wave from the pixel (i,j) in the recording medium is expressed as

$$\boldsymbol{k}_{ij} = \left(-k_0 \frac{x_i}{f}, -k_0 \frac{y_j}{f}, \left[(nk_0)^2 - \left(k_0 \frac{x_i}{f} \right)^2 - \left(k_0 \frac{y_j}{f} \right)^2 \right]^{1/2} \right), \qquad (1)$$

where k_0 is the angular wavenumber of the light in vacuum and n is the refractive index of the recording medium. Thus the overall interference of all waves from the SLM can be regarded as a superposition of the simple interference of two plane waves, so long as the response of the recording medium is linear. Gratings were written by the interference of all combinations of pairs of plane waves from all of the ON pixels in the SLM.

In the readout process, plane waves from the reference pixels were diffracted by all existing gratings in the recorded medium. Here let us consider diffraction of a plane wave from a pixel (k',l') by a grating $\boldsymbol{K}_{klij} = \boldsymbol{k}_{ij} - \boldsymbol{k}_{kl}$, which was written by the interference between the waves from a data pixel (i,j) and a reference pixel (k,l). The diffracted field can be calculated based on coupled wave theory.[5] Under the infinite-plane-wave approximation, Bragg mismatches along the x and y directions are not allowed, i.e., $\Delta k_x = \Delta k_y = 0$, and the wave vector of the diffracted light is the same as $\boldsymbol{k}_{(k'+i-k)(l'+j-l)}$. We assumed that the diffracted wave was detected only by the pixel $(k'+i-k, l'+j-l)$ of the detector array. Thus, the Bragg mismatch was obtained as

$$\Delta k_z = (k_{k'l'z} + K_{klijz}) - \left[(nk_0)^2 - k_{(k'+i-k)(l'+j-l)x}^2 - k_{(k'+i-k)(l'+j-l)y}^2 \right]^{1/2}. \qquad (2)$$

To obtain the light intensity detected by the pixels of the detector array for given data-pixel and reference-pixel patterns, we summed all beams coming from the ON reference pixels and diffracted by all existing gratings. Note that in our calculation we took account of only the gratings formed between a data pixel and a reference pixel to avoid escalation of the required calculation time. We ignored the gratings formed between data pixels and those between reference pixels because the contribution of these gratings was considered to be relatively small.

Some results of the calculation are shown in Fig. 2, together with experimental results. All parameters were the same for both calculation and experiment. The calculation results show good agreement with the experimental results and well represent the differences in the reconstructed image depending on the reference patterns. The uniformity of the image is better for a radial-line reference pattern [Figs. 2(a) and 2(b)]. The haziness observed at the center of an image with a multiple-ring reference pattern is well reproduced in the calculated results [Figs. 2(c) and 2(d)].

Here, to clarify the image formation process, let us consider the diffraction by a single grating $\boldsymbol{K}_{klij}$ illu-

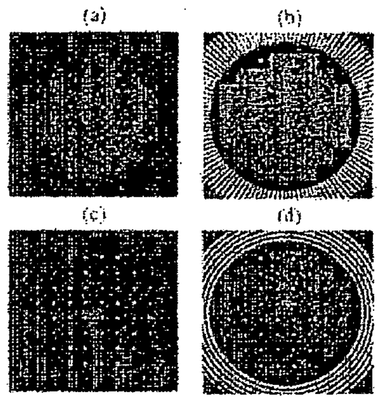

Fig. 2. Comparisons between calculated and experimental results. (a) Calculated and (b) experimental results of the image for a radial-line reference pattern. (c) Calculated and (d) experimental results of the image for a multiple-ring reference pattern.

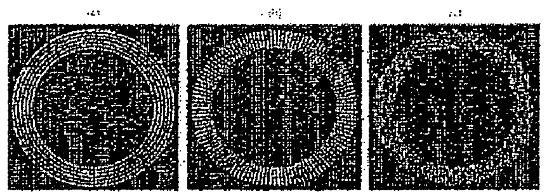

Fig. 3. Diffracted light pattern produced by a single grating written by a data pixel at the center and a reference pixel indicated by the circle. (a) Multiple-ring, (b) radial-line, and (c) random reference patterns. The diffracted patterns are (a) a solid line, (b) a dotted line, and (c) a random dotted line corresponding to the illumination pattern.

minated by the reference pixels. In an ideal case, the diffracted light should reach only the data point (k,l). However, for certain data points that maintain the condition

$$|\boldsymbol{k}_{k'l'} \cdot \boldsymbol{K}_{klij}| = |\boldsymbol{K}_{klij}|^2/2, \qquad (3)$$

Δk_z becomes nearly zero even for $(k',l') \neq (k,l)$. This is called Bragg degeneracy.[7] Because of this effect, the diffracted light pattern is line shaped, as shown Fig. 3, in which reference patterns are (a) multiple rings, (b) radial lines, and (c) random. The width of the lines is determined by the Bragg selectivity. The lines appearing in Figs. 3(b) and 3(c) are broken according to the shape of the reference patterns.

An actual reconstructed image of one data pixel (i_0,j_0) can be obtained by summing the complex amplitude of the line-shaped diffracted pattern over all gratings written by the interference between the data pixel and the reference pixels. The Bragg mismatch of the wave diffracted to the pixel (i_0,j_0) is always zero for all gratings $\boldsymbol{K}_{kli_0j_0}$, though the light intensity diffracted to other pixels is negligibly small unless the Bragg degeneracy condition is maintained. Thus the image of the single data pixel has a peak at the target pixel but spreads slightly to neighboring pixels.

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Now we define a pixel spread function (PxSF) as the complex amplitude of the optical field imaged at the detector array, so long as the response of the recording medium is linear. The PxSF has a function similar to the point spread function (PSF) normally used in linear imaging systems. Once the PxSF is obtained, the optical field at each pixel of the detector array can be calculated by the convolution of the object pattern of the signal pixels and the PxSF, so long as the response of the recording medium is linear. Note that the PxSF of the holographic data-storage system is a complex function that represents the amplitude of the image of a point object due to coherent illumination. Note that the PxSF gives an estimation of intrapage cross talk, though interpage cross talk could be calculated with the same principle of the simulation. That will be our future work.

Some examples of calculated PxSFs are shown in Fig. 4. Although the PxSF is a complex value, only the intensity is shown in Fig. 4. The illumination patterns were multiple rings, radial lines, and random patterns. Figure 4(a) shows the results when no phase modulation was applied by the SLM. The spread of the pixel image is the largest for the multiple-ring reference pattern (filled circles), and the intensity at the neighboring pixel is the smallest for the radial-line reference pattern (crosses). For the random reference pattern (open rectangles), the shape of the plot is similar to that for the multiple-ring reference pattern, but the value is less than one tenth.

We now consider the reason for these differences. For the multiple-ring reference pattern, the pattern of light diffracted by a single grating extends like a line [Fig. 3(a)], and the PxSF is calculated by the summation of these lines, whose direction varies according to the gratings. On the other hand, for the radial-line reference pattern [Fig. 3(b)], the diffracted pattern is a line of dots. In this case the light intensity at the pixel neighboring the target pixel is always very close to zero when all gratings are summed, and the PxSF becomes quite sharp. The two peaks at both sides seen in Fig. 4(a) correspond to the next line of the reference pattern in Fig. 3(b). For the random reference pattern, the neighboring pixel is either bright or dark, depending on the ratio of the numbers of ON and OFF pixels, and the intensity is between those for the multiple-ring and radial-line reference patterns.

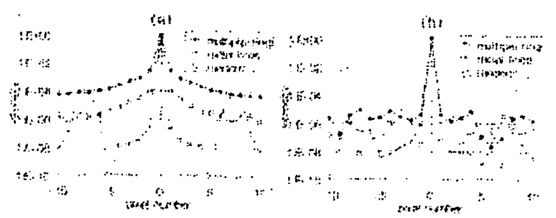

Fig. 4. Calculated intensities of the PxSF (a) without and (b) with random phase modulation: •, multiple-ring; ×, radial-line; □, random reference patterns.

Figure 4(b) shows the results when a random phase is added to each reference pixel. In these cases, all the waves arriving at the target pixel have the same phase and are thus added constructively, because the gratings are read out by the reference pixels used for writing the gratings with the data pixel. The waves diffracted by the gratings and read out by incorrect reference waves have random phase and diminish to zero by averaging during the summation process. That is why the PxSF curves shown in Fig. 4(b) all have quite sharp peaks. The improvement for the multiple-ring reference pattern is particularly significant. We examined the difference of the PxSF at the center, middle, and outer positions of the data area. The difference is quite small for the radial and random reference patterns. The peak value of the PxSF at middle and outer positions is slightly smaller than that at the center. The spread of the PxSF becomes larger with increased distance from the center.

In summary, we have proposed a simple calculation model for image formation in a collinear holographic storage system. The model allows the writing and reading processes in the system to be elucidated. We have also proposed an image evaluation metric called the pixel spread function, which is similar in concept and function to the point spread function used in linear imaging systems. Even a simplified model with some approximations gave results in good agreement with experiment. The model revealed why the radial-line and random reference patterns gave good experimental results and also predicted that an additional random phase in the reference pixels improves the imaging performance. Though we can discuss the qualitative properties of the images in the collinear system with our model at present stage, we can discuss the relative properties of the system when some of the system parameters are changed. In future work we will calculate and discuss the interpage cross talk with our model. Also, we will improve our model by including the effects of reflection gratings and overlapping each plane wave from the pixels and other effects in the next step.

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References

1. H. Horimai, X. D. Tan, J. Li, and K. Suzuki, Jpn. J. Appl. Phys. Part 1 44, 3493 (2005).
2. H. Horimai and X. D. Tan, Opt. Rev. 12, 90 (2005).
3. H. Horimai, X. D. Tan, and J. Li, Appl. Opt. 44, 2597 (2005).
4. C. S. Williams and O. A. Becklund, *Introduction to the Optical Transfer Function* (SPIE, 2002).
5. A. Yariv and P. Yeh, *Optical Waves in Crystals* (Wiley, 1984).
6. S. S. Orlov and L. Hesselink, J. Opt. Soc. Am. B 20, 1912 (2003).